

## ***Interactive comment on “Integrating field, textural and geochemical monitoring to track eruption triggers and dynamics: a case-study from Piton de la Fournaise” by Lucia Gurioli et al.***

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Dear Amanda,

Thanks a lot for your comments and corrections. Please find here our detailed list of responses and the manuscript attached with all the corrections and the new figures

“It would be interesting to see how that permeability data adds to the interpretation of eruptive activity. Also, I think it would also be a more intuitive measurement than isolated/connected vesicularity. “

We added now the permeability data in the Supplementary material (Table S3), as

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you suggested, and we added a new Figure 6d. We didn't add the permeability in the submitted version because we had a limited dataset of only 6 measurements. Moreover, we checked them again and we had to remove one, because we found some epoxy that infiltrated the sample during its preparation. The clasts are quite fragile for these measurements, so we lost a lot of samples. However, the measurements on 2014 clasts performed on one spiny opaque, one spiny glassy, one fluidal clast and two golden pumice (all collected at the Main Vent site) are consistent with the data that we obtained for other PdF eruptions (2015-2016 and 2017, that I am not inserting in this paper because they are part of another project of our PhD student). In the diagram in Figure 6d, we added also the data from February 2015, for comparison (that is: three samples, two fluidal and 1 spiny fragments). The raw data can be found also in the DynVolc database (2017). As you can see from Figure 6d, all the clasts, fluidal, golden or spiny scoria, are quite permeable, independent on their vesicularity, crystal content or of the presence of isolated vesicles. This is in agreement with our interpretation that magma degasses during its ascent in the conduit and that promotes microlite nucleation before magma fragmentation (see also Di Muro et al. 2015 with the Pele's hairs and tears samples for the three 2008 eruptions). Moreover, we often find that the spiny clasts (especially the opaque ones) are slightly less permeable than the golden and fluidal ones, but not as impermeable as you would expect by their low vesicularity. In conclusion, we completely agree with the findings of the publications that you listed. We discuss these findings in the results and discussion sections and we added the references that you suggested. We can see that i) the crystals lower the percolation threshold and stabilize permeable pathways and ii) permeability develops during vesiculation through bubble coalescence, which allows efficient volatile transport through connected pathways and relieves overpressure (Lindoo et al. 2017). We also agree that pervasive crystal networks also deform bubbles and therefore enhance outgassing (Oppenheimer et al., 2015). Based on Saar et al., (2001) you suggest that crystals should start to affect the behavior of the exsolved volatile phase when they approach 20 vol% (Lindoo et al; 2017). In our dataset, apart from the golden and part

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of fluidal, all the other clasts do have microlites >20% (lines 845-854). Our data completely agree that slow decompression rate allows more time for degassing-induced crystallization, which lowers the vesicularity at which bubbles connect (lines 854-857 and more). However, in the crystal-poor fragments we do NOT see a decrease in (i) vesicularity, (ii) number of vesicles, and (iii) permeability (see discussion from lines 858-874). We do not have evidence from the natural samples that the crystal-poor fragments remain impermeable after quenching, due to melt relaxes and pathways closure, as revealed by experiments (Lindoo et al., 2016). The only evidence of this relaxation process could be the high percentage of isolated vesicles in the fluidal and golden fragments due to rapid re-annealing of pore throats between connected bubbles due to short melt relaxation times (Lindoo et al. 2016). However, as explained later to the third review, we doubt about these relaxation process. It would be great to see these samples in 3D, because it is difficult in 2D to say which the isolated vesicles are. What we see in the crystal-poor samples is that permeability increases rapidly once the percolation threshold has been reached, and efficient degassing prevents bubble volumes from expanding past the percolation threshold (Rust and Cashman 2011). In our samples, in fact, we do not have strong evidences of expansions and coalescence.

“I would like to see a more detailed discussion of the crystallinity data given the large impact of crystals on bubble deformation, connectivity/permeability (Spina et al. 2016, Lindoo et al. 2017), volatile distribution in the conduit (Parmigiani et al. 2011, Parmigiani et al. 2016), and ultimately eruptive style.”

We agree with these comments and we added all the crystal percentage expressed as total crystallinity in 3D, using the Higgins program and CSD corrections. The corrected crystallinity for the porosity for mesocrysts and microcrysts percentage (found with Higgins), for plg and cpx are reported now as ranges in Figure 4 and we added the data in Table 3, for each sample, and we deleted the isolated-vesicle column. We expanded the methodology (lines 280-286), results (lines 460-468) and discussion (lines 878-897) paragraphs.

C3

“I did not come away with a clear understanding of their first (i: why was such a small volume of magma erupted instead of forming an intrusion) or fifth (v: What was the time and space evolution of the eruptive event) objectives.” From the comments of all reviewers (Amanda, Madison and the unknown reviewer), it is clear that we had to improve the discussion paragraph. We agree that these two points (and other as well, like the trigger mechanisms) needed to be reframed and expanded. In terms of small eruption versus intrusion and precursor intensity and duration, we summarize here below our reasoning. Let's start to speak about the trigger mechanisms of PdF eruption and the constraints provided by our dataset. An eruption of a shallow system like PdF can be triggered by either internal processes or external processes or a combination of both External processes: (i) Shallow magma reservoir pressurization because of volume changes related to either new magma input and/or to fluid inputs (CO<sub>2</sub>-rich fluids) from deeper magmatic levels. (ii) Heating and enhanced convection of the shallow magma reservoir (energy transfer without fluid or mass transfer). (iii) Pressurisation (volcano inflation) and/or depressurization (volcano deflation) of the hydrothermal system located between the Dolomieu crater and the roof of the shallow magma reservoir. Expansion of the hydrothermal system is due to inputs of heat and fluids from the magma reservoir or deeper and pressurization is favored by its sealing (because of mineral precipitation; lava accumulation at the volcano top). (iv) Deformation of the volcanic edifice and decompression of the magma reservoir and/or hydrothermal system due to flank sliding. (v) Deformation of the volcanic edifice due to deep magma transfers

Internal processes (vi) Accumulation of bubbles in magma recently emplaced in a shallow reservoir at low pressure. (vii) Rapid volatile exsolution (water-dominated fluids; second boiling) after slow magma cooling and extensive crystallization and evolution.

Process (i): Geochemical (bulk rock) and petrological (mineral composition and zoning) data permit to exclude the first hypothesis. The magma erupted in 2014 results to be one of the most evolved and cold magmas ever erupted at Piton de la Fournaise

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(Figs 8 and 10); it is very homogeneous (Fig. 7), minerals do not exhibit reverse zoning and their compositional evolution from phenocrysts to microlites record magma cooling and final degassing (new Figure 10b). Process (ii): is very slow because of slow heat diffusion and 2014 minerals do not record evidences of slow magma heating. About process (iii): The June 2014 eruption was preceded by a weak inflation only 11 days before the eruption. We attributed the summit cone inflation to the pressurization of a very shallow magmatic source (ca. 1.4-1.7 km below volcano summit) by Peltier et al., 2016. On one side, Froger et al., 2015 suggest that PdF hydrothermal system (and its potential sealing as well) was largely disrupted during the 2007 caldera collapse. Lénat et al. (2011) consider the hydrothermal system as a possible eruption trigger. In Lénat's model, thermal expansion of heated geothermal fluids induce rock fracturing by pore pressure increase. Hydrothermal fracturing would cause transient decompression of the magma reservoir, thus triggering vesiculation and starting magma ascent process. However, we found no evidences of new inputs of magma or fluids in the 2014 reservoir, that would have induced the pressurization of the hydrothermal system. Process (iv): finally, geodetic data show no evidence of flank sliding able to produce of the hydrothermal and magmatic system Process (v): The occurrence of deep (>10 km bsl) lateral magma transfer since March-April 2014 has been inferred by Boudoire et al., 2017 (GRL) on the basis of deep (mantle level) seismic swarms and soil CO<sub>2</sub> emissions on the distal western volcano flank. We suspect that these deep processes can have modified the shallower crustal stress field and favored magma vesiculation and eruption trigger. On one side, the 2014 eruption was the first of a long list of eruptions in the 2015-2017 period. On the other side, geophysical and geochemical data have permitted to track vertical magma and fluid transfer below the volcano summit in April 2015, that is about one year after the deep lateral magma transfer (Peltier et al., 2016). Deep processes cannot be detected by the OVPF geodetical network. The 11 days of weak summit volcano inflation, which preceded the 2014 eruption, possibly result from volatile exsolution and expansion of both the shallow magma reservoir and the hydrothermal system. Process (vi): Barometric data (Di Muro et al., 2014; 2016)

C5

suggest that most magma reservoirs feeding the PdF eruptions are stored at shallow pressure (< 1-0.5 kbar). Water exsolution is strongly favored by low pressure and accelerates during magma transfer towards the surface. The 2014 magma erupted after an unusually long phase of quiescence and is chemically evolved, and records extensive magma cooling and crystallization. Extensive crystallization, clearly recorded in 2014 lava (we added the lava data in Figure 4 and in the text), can drive melt migration, volatile concentration and create the conditions favorable to second boiling (Tait et al., 1989). However, we suspect that stress field change related to deep magma transfer induced second boiling and rapid magma vesiculation and expansion, because the 2014 event represented the first of a long series of eruptions, whose magmas became progressively less evolved in time (Coppola et al., 2017). Process (vii): We stress that second boiling is possibly not the only process driving magma foaming in the reservoir. This is because we observe similar textural heterogeneities in 2009 and 2014 eruptive products, which represent the two chemical end-members of recent PdF activity.

Therefore, we suspect that magma storage at shallow depth favors volatile (mostly H<sub>2</sub>O) exsolution at several steps during magma ponding, cooling and evolution and promotes fast magma response to external triggers (stress field changes; magma inputs). Without this external input we believe that the little reservoir of 2014 would have evolved in an intrusion (see the pervasive crystallization of the lava, one of the densest emitted from 2014 to 2017, see Figure 13 in Harris et al; 2017 + unpublished data, below)

See new Conclusions paragraph

In term of space and time evolution of eruptive dynamics and textures, we agree with Madison that we need to add a scheme to summarize our conclusions. We provide the new Figure 12

"The authors employ circularity to characterize different clast types. First, how many particles of each typology were measured using the Morphologi G3? I would also sug-

C6

gest the use of at least three shape descriptors, as recommended by Liu et al. 2015, to fully describe particle morphologies. Currently, the use of a shape descriptor in the interpretation of the eruptive products comes across as an afterthought. Because circularity is not really utilized in the description/interpretation of the products, the section could just be removed. “

We removed the Morphology G3 data, because these data are not so relevant for the whole story of the paper. In the submitted paper, we just wanted to show the methodology and the potential of these analyses. The instrument can measure up to 2000 fragments, so it is very robust in terms of statistics.

“I do think it would be interesting to see if other shape descriptors (such as solidity and convexity) may better describe the relationships between particle shapes and eruption styles.”

We removed these data, but we completely agree with Amanda and we will use her precious comments for another paper (in progress) in which we discuss the ash dataset.

“Why were only 25 clasts from the Western Fracture analyzed versus 146 from the Main Vent? I’m speculative whether the number of clasts accurately samples the Western Fracture explosion. “

We explained the sampling strategy better (see from line 199) in the paper now, in order to clarify all these points and we moved the sampling strategy in the Methodology section. I would like to outline here, however, that three days after the eruption, when the deposits were still hot, difficult to reach etc, the strategy of the OVPF people was to collect as many samples as they could to be representative of the deposits. We stressed in the paper that the deposit from the Western Fracture were formed by scattered bombs and lapilli scorias, all fluidal and we believe our sampling is representative. To show the deposit at the Western Fracture we readjusted Figure 3c

“Also, I do not find it clear how clasts were picked for analyzing vesicle size distributions.

C7

I find the Spiny Glass and Golden pumice density distributions to be slightly bimodal (Fig. 6c). Do the stars in Fig. 6 denote the mode determined for each component? This should be noted in the figure caption as well.”

We explain it better in the text (lines 286-295), in the caption of Figure 6 and in the Figure 6. The choice of the clasts was made mostly on the typologies, rather than on each density distribution, in order to avoid the analysis of clasts with transitional characteristics. For example, two golden pumice fragments were selected from the largest clasts that were the less dense and didn’t break, even if the values in vesicularity were similar. A larger number of fluidal fragments were chosen (even if the density distribution was unimodal) because this typology of clasts was the most abundant and was emitted all along the active fracture, so we did our best in order to study products representative of the Western Fracture, the Upper Fracture and the Main Vent activities. Only one spiny glassy and one spiny opaque were selected, because they were emitted only at the Main Vent.

“I do not see a table that includes all of the crystallinity data (vol.Crystallinity data could be inserted into Table 3 in the connected vesicle or isolated vesicle column, as it’s not necessary to have both (connected/isolated) listed. There is some description in the results (phases present), but I find it difficult to follow without a table to reference/compare. “

The total crystallinity corrected for the porosity, and mesocrysts and microcrysts percentage (found using Higgins software) for plg and cpx are reported now as ranges in Figure 4 and we added for each sample the data in Table 3 as well.

“I would also be interested to see the phase abundances and aspect ratios. The amount of crystals (specifically high aspect ratio plagioclase) coupled with the vesicularity data, may give more insight into efficient vs. inefficient degassing in the different typologies (see Shea et al. 2017). The amount of crystals (depending on the aspect ratio) will influence degassing as well (Lindoo et al. 2017). “

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Yes, we agree with these observations and actually the microcrysts that formed in the conduit are mostly sodic plagioclases; their abundance increases from the golden (high vesicularity and high vesicle number density) to the spiny (lower vesicularity coupled with lower vesicle number density); therefore, the increase in plg of microlites does favour an efficient degassing in the relatively crystal-rich magma, because of their low wet angles that favor degassing against nucleation (Shea 2017). We added and discussed these data in the text and we added Figure 10a.

“I would ask the authors to also consider the effect of crystals on the permeability of the “degassed, cooler reservoir” along with their interpretation of reservoir tapping. Crystals increasing bubble connectivity/permeability of the reservoir alone may contribute to extensive degassing and shifts in eruptive style.”

Yes we do agree that syn-eruptive degassing is favored by bubble connectivity/permeability in the ascending magma, enhanced by syn-eruptive crystallization in the conduit (especially microcrysts of plg), even for magma at low vesicularity. However, we also support the idea of magma stratification in the reservoir. This stratification is probably mechanical and enhanced by melt-crystal separation during second boiling. From the data is evident that we have a melt (represented by golden and large part of the fluidal fragments) with scarce crystals. This crystal poor melt represents only a small volume and is associated (and followed in time by) with the main volume of magma that contains a larger amount of mesocrysts and forms the main volume of the lava flows. These larger crystals, absent in the golden, scares in the fluidal and more abundant in the spiny and lava consist in an equal percentage of plg and cpx and minor olivine, and they form in the reservoir, as shown by their different composition in respect to the microcrysts counterparts (we added a graph of plagioclase compositions, in Fig. 10) that formed in the conduit. However, a large amount of microcrysts in lava formed in the reservoir as well (as shown by their compositions, see Figure 10a). So, we have a range of crystallization conditions. The fact that the lighter plg are not concentrated in the upper portion can be due to the fact that often they are

C9

locked in clusters with the cpx and/or trapped by the microcrysts that in lava formed in the reservoir (see Figure 10a). Our dataset permits us to propose that the 2014 eruption was fed by a physically zoned magma reservoir with the lighter crystal poor magma erupted first (and possibly located in the upper part of the storage system) that ascends faster and feed the more energetic phase, the fountaining. This lighter magma is not more evolved than the spiny one (same bulk compositions) and it is not necessarily richer in dissolved volatile amounts; it is just poor in crystal. We conclude that the second boiling is responsible of the extraction of bubble rich melt from a crystal rich network. This last one will represent the main volume of erupted lava. Fast ascent of the foam hinders its crystallization and preserve high number of vesicles, high vesicularity and it is only little modified by post-fragmentation expansion. Decrease in initial overpressure translates in a progressive decrease in magma ascent rate and output rate (e.g. Coppola et al., 2017 and references therein). Nucleation of microcrysts is enhanced in melt ascending with lower speed and is mostly related to syneruptive degassing (for the spiny). The larger volume (dense lava) corresponds to crystallized and less vesiculated magma which experiences a slow ascent in the dyke and even further micro-crystallization during its subaerial emplacement.

“Section 5.2 might benefit from subsections or reorganization, perhaps divided by the different typologies, sampling area, or interpretation and comparison to other studies. There is a lot of information presented and comparison to other studies.”

We did it, also following Madison suggestions. See the new 5.2 paragraph subdivided now in four subsections: 1) Background on the texture of clasts from Hawaiian and Strombolian activities; 2) The four typologies of clasts and their distribution in space and in time in the 2014 eruption at Pd; 3) Degassing-driven versus cooling-driven crystallization 4) Textural syn-eruptive versus post fragmentation modifications

“Lines 99-105 – Reassess/reorganize the questions posed here. There are 5 questions listed with (iv) and (v) attached to (iii). I suggest separating each question with a paragraph or do not separate them. Also, I do not think questions (i) or (v) were

C10

addressed in the discussion/conclusions section.” We addressed these two questions now, see the new conclusions

“Table 3 does not need both connected vesicularity and isolated vesicularity listed.” We deleted a column and we added the crystals parameters

“Figure 5c needs a more descriptive caption. I’m not sure what I and II refer to or the arrows (the clasts pictured?). I think the caption only describes one of the two graphs?” Figure 5c was removed

“Figure 6c – please clarify the meaning of the star symbols” We clarify it in the caption and we improved the figure

“Figure 11 could be redrafted to provide more clarity to the reader. I would move the references to the figure caption to make room for an inset similar to Stovall et al. 2011 to help the reader interpret trends.” We did it, see new Figure 11

“89 references - I think the number of the references could be reduced.”

I don’t think that in a paper where we integrated field, physical textural, petrological and geochemical analyses we can reduce the references. With the corrections and the suggestion from the three reviewers we actually increased the references list. If the journal does not impose references limitations we are happy to try to acknowledge all the relevant contributions

“Is the amount and quality of supplementary material appropriate? Yes. Some formatting issues with supplementary tables.” Yes, we readjust all the tables.

“Line 111 – I would recommend removing this final sentence. The authors make it clear earlier in the introduction the importance of the multi-disciplinary approach.” Yes, we removed it

“Line 218 – Should reference Fig. 3e not 3f?” Yes

“Line 310 – Combine the two sentences with the rest of the paragraph.” Yes, corrected

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“Line 331 – Should reference Figure 3b?” Yes, thank you

“Line 510 – subscript “wr” in MgOwr.” Yes, corrected

“Line 645 – reference numbers for comparison to Houghton et al. 2016. General - Vg/VI should be Vg/VI. Subscript “v” in Nv.” We corrected it

“Figure 1 – An inset map of Reunion Island would be helpful. (1c) is very dark/difficult to see.” Done

“Figure 3c – The pictures are so small it is difficult to see.” We changed a lot in Figure 3, to better clarify the nature of the deposits

“Figure 3e – 2010, Fountaining is spelled wrong.” We corrected it

“Figure 10 – Inconsistent figure formatting. Thick axes lines and bold axes values” We corrected it

“Missing or incorrect references:” Bombrun et al. 2015 (line 703) Added

Di Muro et al. 2012 (line 126) Deleted

Gurioli et al. 2008 (line 633) Added

Hammer et al. 1999 (line 750) Added

Inman 1952 (line 223) Added

Liuzzo et al. 2015 (line 134) Added

Morandi 2015 (line 72) Corrected

Line 58 – Taddeucci misspelled Done

Line 60 – Extra “and” Corrected

Line 60 – Eychenne misspelled. Corrected

Line 61 – Should read “Leibbrandt and Le Pennec, 2015”. Corrected

C12

Line 600 – references in italics. Corrected

Line 971 – Should read “Lange, R.A.,. . .” Corrected

Line 1016/1020 – reference chronology inconsistent. Corrected

Line 1023 – delete “a” from reference. Corrected

References cited:

Lindoo, A., Larsen, J. F., Cashman, K. V., and Oppenheimer, J., 2017, Crystal controls on permeability development and degassing in basaltic andesite magma: *Geology*, 45(9), p. 831-834.

Liu, E. J., Cashman, K. V., Rust, A. C., 2015, Optimising shape analysis to quantify volcanic ash morphology: *GeoResJ*, 8, p. 14-30.

Parmigiani, A., Huber, C., Bachmann, O., and Chopard, B., 2011, Pore-scale mass and reactant transport in multiphase porous media flows: *Journal of Fluid Mechanics*, v. 686, p. 40-76.

Parmigiani, A., Faroughi, S., Huber, C., Bachmann, O., Su, Y, 2016, Bubble accumulation and its role in the evolution of magma reservoirs in the upper crust: *Nature*, 532,p. 492-494.

Spina, L., Cimarelli, C., Scheu, B., Di Genova, D., and Dingwell, D. B., 2016, On the slow decompressive response of volatile- and crystal-bearing magmas: An analogue experimental investigation: *Earth and Planetary Science Letters*, v. 433, p. 44-53.

We checked these papers and we added a few references from the list above and other useful ones founded in the papers

Please also note the supplement to this comment:

<https://www.solid-earth-discuss.net/se-2017-99/se-2017-99-AC2-supplement.pdf>

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Interactive comment on Solid Earth Discuss., <https://doi.org/10.5194/se-2017-99>, 2017.

C14

[illegible]

**Fig. 1. Table S3**